

## MESOZOIC CLIMATE

## Liverworts and all

The relationship between carbon dioxide and climate over millions of years has been a source of controversy. Fossilized liverwort leaves can help illuminate both temperature and atmospheric carbon dioxide levels from 200 to 60 million years ago.

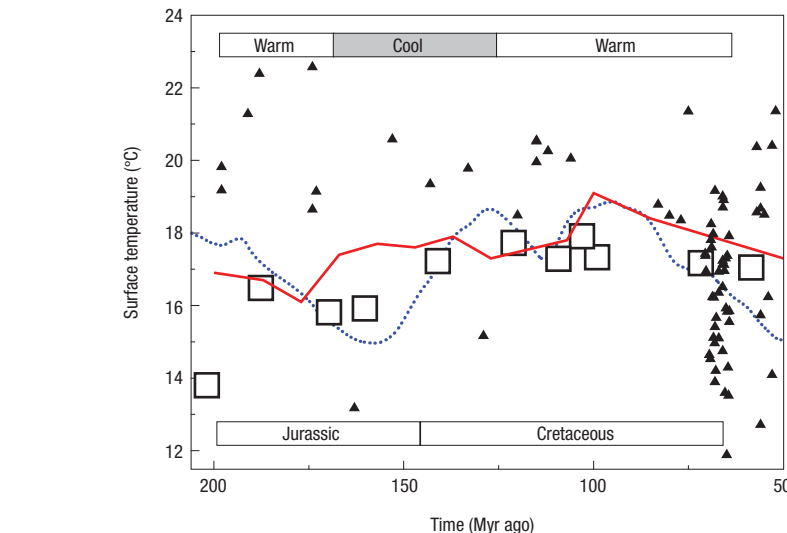
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Reconstructing global climate and atmospheric carbon dioxide concentrations on multi-million year timescales has been an elusive goal for geoscientists. Various proxies and models suggest that warm climate periods and high levels of atmospheric CO<sub>2</sub> coincide whereas cool periods correspond to lower atmospheric CO<sub>2</sub> levels<sup>1-4</sup>. This has been taken as evidence that the climate evolution over million-year timescales is mainly controlled by natural variations in CO<sub>2</sub> production and consumption. However, some temperature reconstructions have contradicted this view<sup>5,6</sup>. The most striking example for the suggested temperature–CO<sub>2</sub> decoupling lies in the late Jurassic to early Cretaceous periods, when the records indicate cool conditions<sup>7</sup>, despite proxies and models predicting a warm greenhouse climate accompanied by high atmospheric CO<sub>2</sub> concentrations<sup>1</sup>. On page 43 of this issue, Fletcher and co-workers<sup>8</sup> analyse the carbon isotopic ratios of fossil plants and suggest that late Jurassic atmospheric CO<sub>2</sub> levels are much lower than previously believed.

Stable carbon isotope measurements from fossilized soils formed in the Jurassic and Cretaceous periods suggest high levels of atmospheric CO<sub>2</sub> (ref. 3). Models of the global carbon cycle confirm this interpretation and produce a 100 million year period of warm stable climate<sup>1</sup>. However, the distribution of coals, desert and salt deposits, glacial materials, and tropical soils suggest a much more variable climate with at least one pronounced cool episode<sup>6</sup>. Marine records seem to confirm the occurrence of a cold interval during the late Jurassic and early Cretaceous<sup>5,9</sup>. This apparent decoupling of atmospheric CO<sub>2</sub> and climate has led to alternative explanations for climate forcing during this



**Figure 1** Jurassic and Cretaceous surface temperature reconstructions. Temperatures derived from the liverwort-based reconstruction of atmospheric carbon dioxide levels (open squares)<sup>5</sup> are substantially lower than those from fossil soils (closed triangles)<sup>3</sup>, when both sets of  $p\text{CO}_2$  proxy data were converted into average global surface temperatures using the GEOCARB III equation<sup>1</sup>. Temperatures from the pH-corrected marine oxygen isotope records (red solid line<sup>4</sup> and blue dotted line<sup>9</sup>) broadly agree with the liverwort reconstruction. Relatively warm and cool periods are shown in the bar at the top<sup>6</sup>; the timescale is taken from ref. 13.

time, such as changes in the flux of galactic cosmic rays reaching the Earth<sup>5</sup>.

However, climate–CO<sub>2</sub> decoupling need not be assumed as there is a weak link in the chain of arguments for the Jurassic–Cretaceous high-CO<sub>2</sub> greenhouse. Over geological timescales, levels of atmospheric CO<sub>2</sub> ( $p\text{CO}_2$ ) are reconstructed with models based on the marine record of <sup>87</sup>Sr/<sup>86</sup>Sr ratios. Strontium ratios respond to the hydrothermal and volcanic release of CO<sub>2</sub> as well as its consumption through silicate-rock weathering — the main source and sink mechanisms, respectively — with high <sup>87</sup>Sr/<sup>86</sup>Sr ratios suggesting a low  $p\text{CO}_2$  and vice versa. The models yield high  $p\text{CO}_2$  values during the Jurassic period<sup>1,9</sup>, in part because the marine <sup>87</sup>Sr/<sup>86</sup>Sr record over the past 545 million years reaches a well-defined minimum during the Jurassic

period that could indicate high rates of volcanic emissions or low rates of rock weathering. The low <sup>87</sup>Sr/<sup>86</sup>Sr ratios could, however, also be produced by weathering of young volcanic deposits<sup>10,11</sup>. In that case, the low Jurassic <sup>87</sup>Sr/<sup>86</sup>Sr ratios would indicate a low, rather than high,  $p\text{CO}_2$  because CO<sub>2</sub> is rapidly consumed by the weathering of young volcanic rocks.

Fletcher and co-workers<sup>8</sup> take the effect of the weathering of young volcanic rocks on  $p\text{CO}_2$  and the marine strontium record into account in their solution to the Jurassic paradox. They used the carbon isotopic ratios of fossil liverworts to reconstruct changes in  $p\text{CO}_2$  over the Jurassic and Cretaceous periods. On the basis of the fossils, they conclude that in the late Jurassic to early Cretaceous,  $p\text{CO}_2$  was much lower than previously believed. The group also

independently simulated Jurassic and Cretaceous  $p\text{CO}_2$  levels using a model based on the  $^{87}\text{Sr}/^{86}\text{Sr}$  record that accounts for the effect of weathering of young volcanic rocks on the strontium records. This also results in lower than expected  $p\text{CO}_2$  values during the late Jurassic and early Cretaceous periods, in agreement with earlier modelling efforts<sup>10,11</sup>. Of the existing  $p\text{CO}_2$  records, those from liverwort most closely match the simulation, although a reconstruction of  $\text{CO}_2$  from the pores of fossil leaves also yields largely similar results<sup>5</sup>.

The liverwort  $\text{CO}_2$  reconstruction, when converted into temperature, is broadly consistent with the carbonate-based surface temperatures that had sparked earlier debate<sup>5</sup>, and it shows a positive correlation with surface temperatures derived from pH-corrected  $\delta^{18}\text{O}$  values measured in marine carbonate fossils<sup>4,9</sup> (Fig. 1). This correlation might be fortuitous, or it may suggest that ancient  $p\text{CO}_2$  records are better preserved in liverworts than in other archives such as fossilized soils and leaves that have previously been used to reconstruct atmospheric compositions<sup>3</sup>.

Carbon isotope reconstructions from liverworts yield much lower  $p\text{CO}_2$  values and lower surface temperatures than

from fossilized soils over the Jurassic to Cretaceous periods. If they prove to be a reliable archive for ancient  $p\text{CO}_2$  values, the new results raise questions about the validity of the previously used proxies.

Deviations between reconstructions from liverwort and fossil soils could, however, be due to rapid changes in  $p\text{CO}_2$  that are as yet beyond the temporal resolution of the records. For example, the Jurassic and Cretaceous periods could have generally experienced a warm greenhouse climate that was punctuated by multiple discrete cooling events, probably accompanied by rapid changes in  $p\text{CO}_2$  (ref. 3). More liverwort data need to be generated to cross-check the new method with other more established proxies.

Fletcher and co-workers' reconstructions suggest that the Earth's long-term climate history is indeed controlled by atmospheric  $\text{CO}_2$  concentrations. However, the various proxies for both  $\text{CO}_2$  levels and temperatures over million-year timescales do not yet provide an unambiguous picture, leaving models of the global carbon cycle poorly constrained. This is not necessarily surprising; after all, even the modern global carbon cycle is not fully understood. Important feedbacks that may

have far reaching consequences for our understanding of past and future climate change<sup>12</sup> are still being discovered.

It is important for geoscientists to continue to improve proxies and models that help reconstruct the ancient global carbon cycle, while taking into consideration the results of those working on modern carbon cycling and future climate change.

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## ATMOSPHERIC SCIENCE

# Black carbon and brown clouds

In aerosol hot spots around the globe, solar radiation is dimmed down on its way to the Earth's surface. The resulting surface cooling turns out to be almost in balance with heating of the atmosphere due to black carbon.

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**H**ow atmospheric particles — generally termed aerosols — affect air temperatures depends on altitude: they reflect some of the incoming solar radiation back to space, cooling the Earth's surface, and at the same time absorb some of the sun's energy, heating the atmosphere around them. But the magnitude of aerosol energy absorption on the global scale and its contribution to global warming are uncertain. Two related papers by Ramanathan *et al.*<sup>1</sup> and Stone *et al.*<sup>2</sup> tackle the sources of that uncertainty. The first study pulls together a global suite of data and simulations of the

atmosphere to characterize the extent and distribution of atmospheric brown clouds, which are areas of high aerosol concentration. The second paper concentrates on one specific site in the Indian Ocean, seeking to explain the origin of the absorbing aerosols in the brown clouds there.

Black carbon, typically emitted from combustion processes, is the main light-absorbing component of aerosols. The radiative properties of individual aerosol particles depend on the extent to which black carbon is mixed with primarily scattering aerosol components, such as sulphates and organics<sup>3</sup>. The amount of light absorbed by each particle is measured by its single scattering albedo — the ratio between the light extinction due to scattering alone and the total light extinction from both scattering

and absorption. If the single scattering albedo lies below a critical value, the combined aerosol–Earth system reflects less energy back to space than the Earth's surface alone, leading to a net warming of the Earth. But this critical single scattering albedo depends strongly on the Earth's local albedo (that is, its reflectivity) — the more reflective the background to the aerosol, the higher the critical value. Optically thick clouds below an aerosol layer effectively serve as a highly reflective background<sup>4</sup>, so absorption by aerosols is highly sensitive to the vertical distribution of particles relative to clouds.

The effect of anthropogenic aerosols on the global energy budget can be estimated by comparing two climate model simulations — one for present-day and one for pre-industrial conditions — using